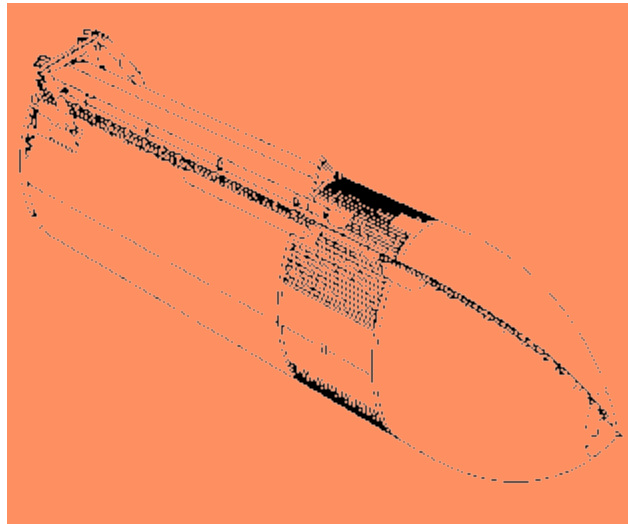


# **Space Shuttle Super Lightweight Tank (SLWT)**

## **Independent Assessment of Risk Management Activities**



NASA Office of Safety and Mission Assurance  
December 12, 1997

## **Executive Summary**

Marshall Space Flight Center (MSFC) and Lockheed Martin (LM) have implemented safety and risk management processes which provide high confidence that the SLWT program will operate safely, achieving mission success.

The SLWT program safety and risk management processes encompass activities of Program Management, Safety & Mission Assurance (SMA), and Systems Engineering. They fulfill every aspect of the NASA Policy Guidance (NPG) document 7120.5A risk management approach. They are consistent with the high level of assurance appropriate for a human-rated aerospace flight system.

Safety hazards and risk drivers have been identified, analyzed, mitigated, controlled or accepted with rigor and diligence. Extensive and rigorous independent assessment (both internal and external) activity has verified and validated issue resolution. The SLWT program's safety and risk management strengths are reflected in their responsiveness to suggestions and recommendations from independent assessment teams and the open and ongoing dialogue concerning safety and risk management issues. The close coordination among engineering, management, and SMA processes serves as an ongoing internal check of process effectiveness.

The OSMA SLWT safety and risk management evaluation team finds that risk issues and other concerns identified by the SLWT program and numerous independent assessment teams have been properly managed and dispositioned. Given the conservative design and test approach, the maintenance of safety margins, and extent and rigor of independent assessment and independent technical analyses we find the SLWT design is safe. With continued strict adherence to critical manufacturing process stability, capability and control (especially weld repair allowables) we are confident that the SLWT will operate safely.

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## **1.0 Background**

In response to direction from the Administrator, the Associate Administrator for Safety and Mission Assurance (SMA) established a team comprised of Mr. J. Steven Newman and Dr. Pete Rutledge of the SMA staff to undertake an independent assessment of the Space Shuttle Program, Super Lightweight Tank (SLWT) safety of flight.

### **1.1 SLWT Independent Assessment Task**

**The independent assessment (IA) was defined as follows:**

“Determine if the combined safety and risk management activities implemented by the Space Shuttle SLWT Program and the prime contractor were properly structured and thorough, and conducted over the program life-cycle in accordance with generally accepted engineering and management methodologies and the risk management process outlined in NASA Policy Guidance NPG 7120.5A.”

### **1.2 Approach**

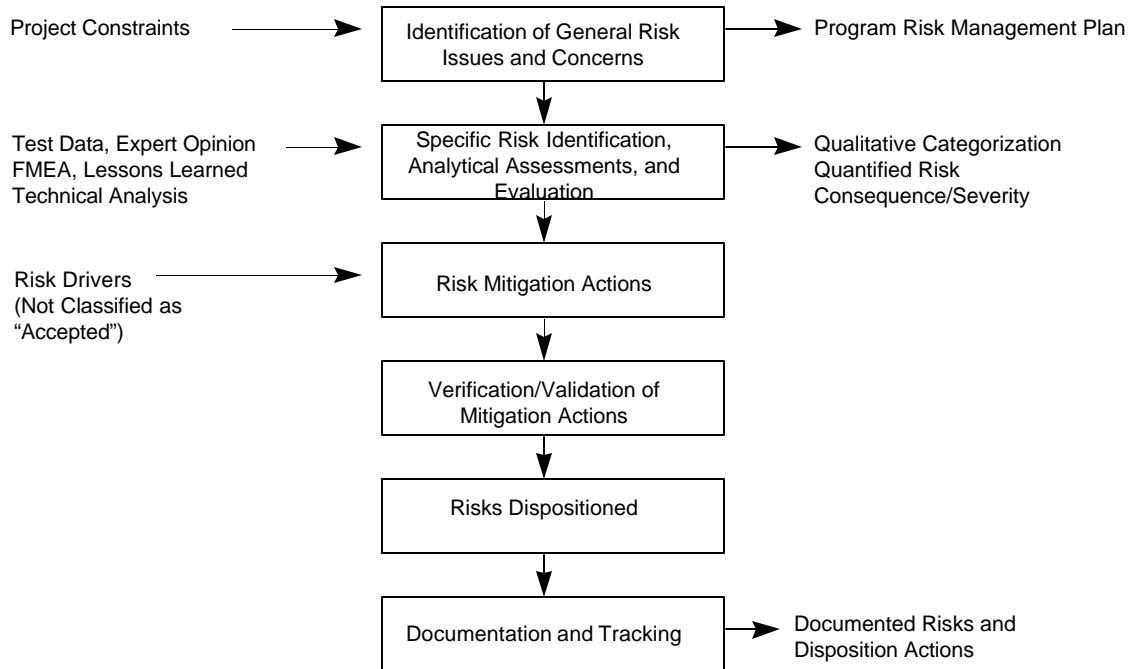
The IA approach was structured to reflect the emerging NASA HQ role of process level “insight,” analyzing and evaluating the fidelity of management, engineering and SMA processes which contribute to safety and mission success. Principal on-site data gathering was conducted in parallel with the SLWT Design Certification Review (DCR) pre-board activity at the Michoud Assembly Facility (MAF), September 20-24, 1997. Interviews were conducted with dozens of “process owners,” managers, engineers and scientists (Lockheed-Martin (LM) and NASA civil servants) directly involved in SLWT design and manufacturing technology development. During the DCR pre-board period, nineteen “macro” processes were identified as key elements in the overall LM Michoud safety and risk management approach. Additional data was acquired subsequent to the DCR activity, in particular, Hazard Reports and the proceedings of the SLWT “Verification Team” activity over a three year period. Extensive review of previous independent assessment findings was carried out with attention to risk identification, mitigation, tracking and closure of all flight safety issues.

### **1.3 NPG 7120.5A Risk Management Process**

Nineteen embedded safety and risk management processes were mapped into the six elements of the Risk Management Process (Figure 1.1) defined in the new NASA Policy Guidance document (NPG) 7120.5A, “NASA Program and Project Management Processes and Requirements.”

# Risk Management Process

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**Figure 1.1**

## 1.4 SLWT Safety and Risk Management Activity

LM and MSFC have employed numerous management and engineering processes which provide an interlocking system of checks and balances to assure safety. Table 1.1 identifies the individual processes and “maps” each process into the NPG 7120.5A risk management elements. It is evident that LM safety and risk management practices and discipline penetrate all areas critical to achieving mission success.

Brief summaries are provided below for several representative “macro processes”: the Hazard Analysis process, the Design Safety Checklist Process and the Operational Readiness Review process. Michoud Space Systems’ systematic approach to safety and risk management provides visibility and confidence that safety considerations have been incorporated into all phases of the product life cycle. The constraints of time, cost, and technical requirements to attain program objectives required progressive application of systematic methods, through an iterative process, to achieve mission success. The LM-MAF risk management concept is graphically depicted in Figure 1.2 which strongly reinforces the notion that risk management is a recurrent activity.

# Mapping of SLWT Risk Management Processes

## Risk Management Process (7120.5A)

<b>MSFC / LM: Process / Practice or System</b>	Preliminary Risk ID	Specific Risk Evaluation	<u>Risk Mitigation Activity</u>	<u>Mitigation Effectiveness Verification</u>	<u>Mitigation Implementation Validation</u>	Documentation & Tracking
P1 - Requirements Documentation & Flowdown Process			<b>X</b>			
P2 - Mission Success Communication Process			<b>X</b>			
P3 - Program Review Processes	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
P4 - Program Control Processes				<b>X</b>	<b>X</b>	<b>X</b>
P5 - Personnel Certification Process			<b>X</b>			<b>X</b>
P6 - Hazard Analysis Process	<b>X</b>	<b>X</b>				<b>X</b>
P7 - FMEA -CIL Process	<b>X</b>	<b>X</b>				<b>X</b>
P8 - Technology Development & Verification Process (Macro-Process)				<b>X</b>	<b>X</b>	
P9 - Technology Development & Verification: Parent Material Acceptance Process			Table 1.1	<b>X</b>	<b>X</b>	<b>X</b>

# Mapping of SLWT Risk Management Processes

## Risk Management Process (7120.5A)

<b>MSFC / LM: Process / Practice or System</b>	Preliminary Risk ID	Specific Risk Evaluation	<u>Risk Mitigation Activity</u>	Mitigation Effectiveness <u>Verification</u>	Mitigation Implementation <u>Validation</u>	Documentation & Tracking
P10 - Technology Development & Verification: Welding Process				<b>X</b>	<b>X</b>	<b>X</b>
P11 - Technology Development & Verification: Weld Repair Process				<b>X</b>	<b>X</b>	<b>X</b>
P12 - Material Review Board Process				<b>X</b>	<b>X</b>	<b>X</b>
P13 - Test & Verification Processes			<b>X</b>	<b>X</b>		<b>X</b>
P14 - Inspection & Surveillance Processes				<b>X</b>	<b>X</b>	<b>X</b>
P15 - Supply Chain Quality Management Process			<b>X</b>	<b>X</b>	<b>X</b>	
P16 - MSFC Special Analysis & Review Assurance Processes		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	
P17 - LM Special Analysis & Review Assurance Processes		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	
P18 - Independent Assessment Processes		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
P19 - Flight Readiness Review and COFR Process		<b>X</b>		<b>X</b>	<b>X</b>	<b>X</b>

Table 1.1 (continued)



## **Hazard Analysis**

Michoud Space Systems' Hazard Analysis process consists of identifying potential hazardous conditions, developing controls to prevent the hazards, verifying the controls are in place, and documenting the results. The involvement of systems safety personnel in all phases of SLWT development and operation ensures timely identification and elimination/control of potential risks to personnel, property, and the environment within the constraints of cost, schedule, and program requirements. SLWT hazard analysis process relies on the established Space Shuttle Hazard Analysis process. SLWT hazards have been reviewed by the System Safety Review Panel and will be entered into the ET Hazard Analysis Report following PRCB approval. Also, the current version of the Space Shuttle Critical Items List (CIL) includes SLWT items.

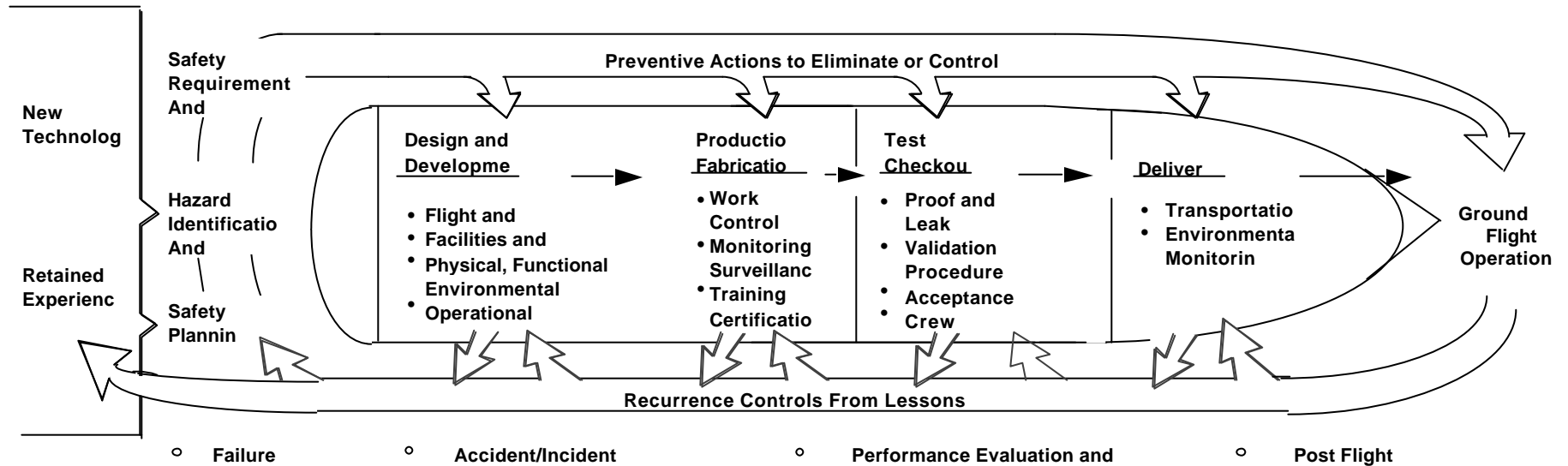
## **Design Safety Checklist**

Michoud Space Systems' Design Safety Checklist is a practical and effective technique for the application of safety experience to the design and operation of hardware systems and equipment. The Design Safety Checklist assists all disciplines in the application and retention of lessons learned; provides a management tool to coordinate the safety program; places safety in the mainstream of events; provides educational benefits to all disciplines; and provides a systematic method to identify hazards which can be used independently or in support of more sophisticated hazard analysis methodologies.

## **Operations Readiness Reviews / Test Readiness Reviews**

Michoud Space Systems' Operational Readiness Inspection (ORI) program verifies the readiness of flight or test articles, facilities, tooling, procedures, and personnel to perform their specified operations. The ORI process is a formalized verification that any critical or potentially hazardous operation is ready to proceed. ORI reviews examine lessons learned, personnel qualifications and training, demonstrated process capabilities and most importantly process failure modes. The ORI process also serves to verify implementation of process fail-safing measures and other failure (and defect) prevention activities. The Test Readiness Review is a closely related preparatory exercise which works hand-in-hand with the ORI to assure the readiness of specific test program activities.

# LM Michoud Assembly Facility Safety and Risk Management



The flow in Figure 1.2 depicts the safety and risk management process as an ongoing and embedded behavior rather than a “single event” or one time activity. The arrows reinforce the notion of documentation and tracking of mitigation measures over the program life-cycle . The LM-Michoud safety and risk management approach is “institutional” in nature, identifying and addressing historic risk drivers and using knowledge gleaned from lessons learned.

Figure 1.2

## **2.0 Background - Introduction to the SLWT**

The Super Light Weight Tank team was tasked with boosting the payload capability of the Shuttle by safely removing 7500 lbs. from the existing 65,400 lb. External Tank (ET). The weight reduction was achieved principally through the use of a new, lower density, higher strength, aluminum lithium alloy, 2195, along with redesign of the skin and stringer structural configuration for the Liquid Hydrogen (LH2) tank. The 2195 aluminum lithium alloy provides approximately 29% increase in yield strength, 15% increase in ultimate strength, 5% increase in modulus and 5% decrease in density when compared to the current 2219 alloy.

The current 2219 aluminum alloy was replaced with 2195 in numerous components as shown in Figure 2.1. Additional weight reduction was achieved through the use of a machined and/or tailored application of thermal protective system (TPS) ablative foam. The major design change contributing to weight reduction was replacement of LH2 barrel panel skin and stringer configuration with an orthogrid panel design.

### **Other Pertinent Data**

The first SLWT, STS-91, (using ET-96) is scheduled to fly on May 29, 1998, (104% engine power) carrying the Spacehab Module to Mir (Mission 9). The second SLWT will be the first International Space Station Assembly flight (Node 1), STS-88 (ET-97) on July 9, 1998 (104% engine power). The third SLWT will boost STS-93 (ET-98), on August 27, 1998, deploying the AXAF observatory (104% engine power). A power setting of 106% may be required on one or more International Space Station assembly missions.

The External Tank has over 3,000 linear feet of welding. This underscores the importance of manufacturing process capability, stability and control (weldability and weld repair), as well as inspection and Non-Destructive Evaluation (NDE) in assuring the fidelity of the completed tank.

### **SLWT Risk Quantification Using Probabilistic Risk Assessment Techniques**

As part of a larger project to develop the NASA Quantitative Risk Assessment System (QRAS), in 1997, MSFC SMA worked with the ET Project Office and consultant Bob Mulvihill to update the 1995 SAIC probabilistic risk assessment (PRA) of the ET. The current LWT version of the ET was remodeled. The results of this most recent work, in terms of the ET's estimated contribution to the risk of a Space Shuttle catastrophic accident (on a per mission basis), yield a lognormal probability density having a median value of 1/7246, a 5<sup>th</sup> percentile of 1/12,629 and a 95<sup>th</sup> percentile of 1/4158. Comparing median values, among the Shuttle elements, the ET contributes less than 3% of the overall Space Shuttle risk of catastrophic accident of 1/205. Over the next 3-4 months, the SLWT will be quantitatively modeled by MSFC. In the January-February 1998 time frame, it will be possible to compare the estimated risk of the two versions of the ET.

# SLWT - Summary of Major Changes from LWT

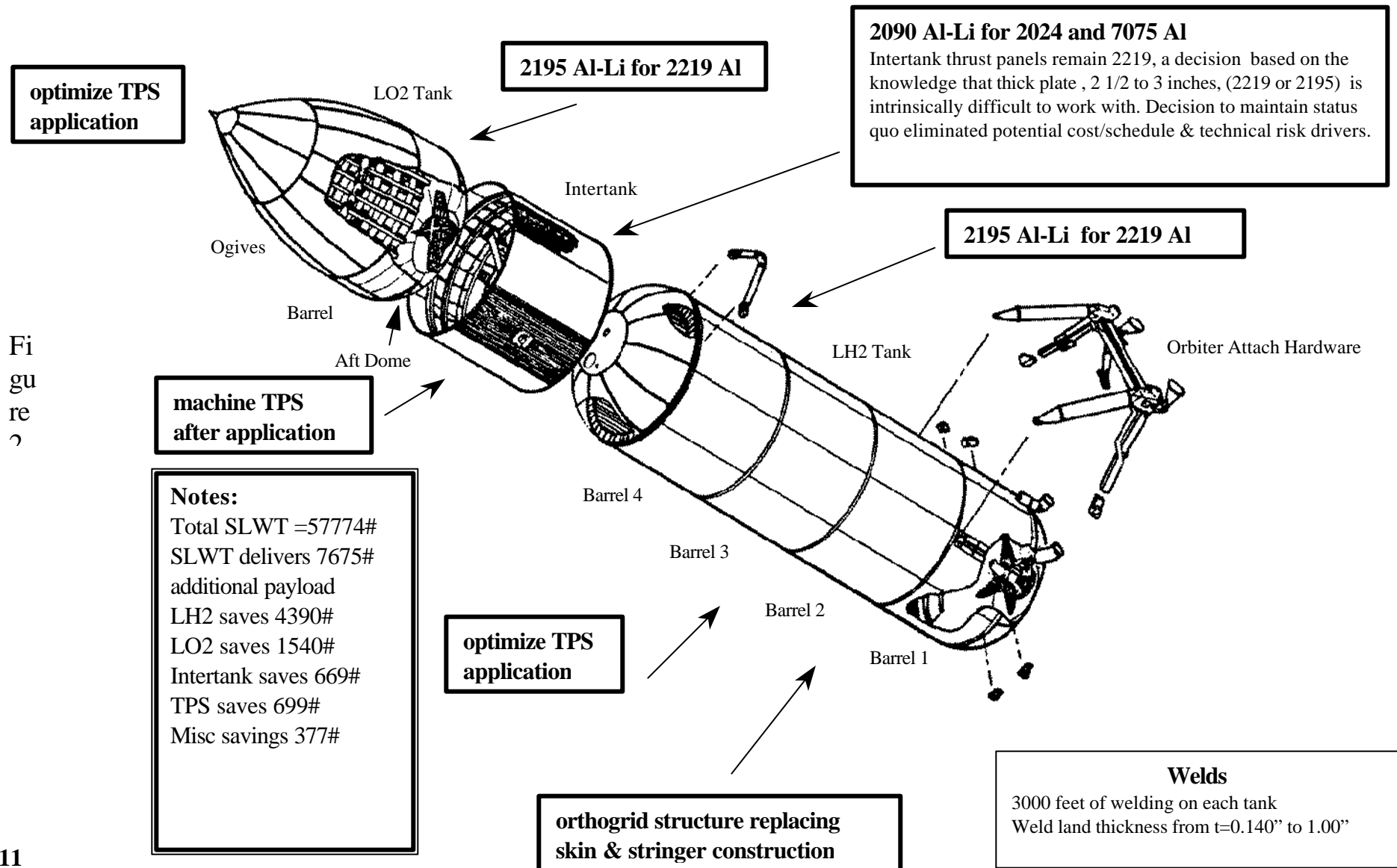


Figure 2

### **3.0 Major Safety and Risk Management Issues, Mitigation Approaches and Independent Assessment**

The following paragraphs identify major SLWT program safety and risk management issues, describe principal risk management approaches and discuss the independent review and assessment activity associated with the particular issue.

#### **Independent Assessment**

The SLWT program has had the benefit of extensive independent assessment activity. The program has been very responsive to suggestions and has benefited accordingly. Appendix A present a chronology of IA activity along with key events and milestones in program development. It is important to note that three types of IA input has supported the program. First, the program has had continuous (“real time”) IA participation by the “Verification Team”, established early in the program. Secondly, the program has been the focus of periodic (yearly) “snapshot” IA review from such teams as the Independent Annual Review , and the Aerospace Safety Advisory Panel (ASAP). Thirdly, there have been a series of one-time reviews, such as the early (1993) Jim Odom, Bob Ryan, and Rick Davis independent assessment reviews. (These reviews established the design verification framework which was ultimately implemented.) Other examples include the 1994 OSMA (Mulville) Review.

All of the IA input and activity has been integrated by the SLWT program and has been continuously monitored by members of the Verification Team. Typically the snapshot and one-time reviews built upon, and in some cases expanded and reinforced, issues which were actively under the review and scrutiny of the Verification Team.

#### **SLWT Verification Team**

The Verification Team monitored and assisted in the implementation of the 1993, Odom/Davis Independent Assessment recommendations and served throughout the program life-cycle as the arbitrator of technical safety and risk management issues related to design, parent material and manufacturing issues. The initial Odom/Davis review provided the verification “compass” that has guided the SLWT verification activity. The membership of the original SLWT Verification Team is shown below:

Robert Ryan	NASA/MSFC	Co-chair
Dennis Deel	LMC/MAF	Co-chair
Frank Boardman	NASA/MSFC	
Neil Otte	NASA/MSFC	
Glenn Miller	NASA/JSC	
Dr. Michael Nemeth	NASA/LaRc	
Gale Copeland	LMC/MAF	

Michael Quiggle	LMC/MAF
Robert Morra	LMC/Retired
Dr. Jackie Bunting	LMC/Astronautics

### **Independent Annual Reviews (IAR)**

IAR's chartered by the Program Management Council, were conducted in 1994, 1995, 1996, and 1997. The IAR forum served to elevate safety and risk management concerns to the Deputy Administrator, the AA/OSMA as well as other senior NASA officials throughout the SLWT development. The IAR maintained a balanced review of both schedule and budget concerns as well as technical safety and risk management issues.

### **Aerospace Safety Advisory Panel (ASAP)**

ASAP conducted status reviews in 1993 and 1994, and in-depth technical reviews in 1995, 1996, and 1997. The ASAP team provided independent review of safety and risk management issues throughout the development of the SLWT. The ASAP team focused on safety of flight issues and provided numerous recommendations concerning parent material qualification as well as welding and design verification. The SLWT technical assessment and evaluation activity of ASAP was spearheaded by:

- Melvin Stone, former Director of Structures at Douglas Aircraft Company,
- Kenneth Englar, former Chief Engineer of Mc Donnell Douglas Corporation and Chief Design Engineer for the Delta Launch Vehicle, and
- Dr. Seymour Himmel, former Associate Director of the NASA Lewis Research Center, and active in aerospace engineering since 1948 when he joined the National Advisory Committee for Aeronautics.

### **Individual Technical Expert Reviewers of the SLWT Development Activity**

Another dimension of the independent assessment assurance role is "degree of independence." That is, from how far "outside the circle" of program development activity does the expert reviewer bring his or her perspective? The challenge is to find individuals knowledgeable enough in relevant technical areas but still outside the cultural influence of the project team driving to meet program cost and schedule goals. The SLWT program has been fortunate to have numerous expert reviewers from outside the project team environment as shown in Appendix B of this document.

### **3.1. Issue: Parent Material Properties**

Comparatively limited knowledge of 2195 material characteristics and weldability (including repair) created a challenging development program. It was necessary to confront and address one technical issue after another, in parallel with design and manufacturing development activity. Parent material issues included manufacturing variation and instability, fracture toughness and lowered properties in the short transverse direction.

### **3.1.1 Mitigation Approaches**

#### **Acceptance Testing**

Rigorous material acceptance testing approaches have been implemented which incorporate ultrasonic testing (particularly important for detecting laminar flaws, i.e. volumetric flaws parallel to surface) of all material raw stock, as well as strength, conformity (to specification requirements) and fracture acceptance testing on every lot.

#### **Fracture Control (Testing to Verify Flaws Will Not Propagate)**

Each lot of 2195 aluminum lithium undergoes “simulated servicing testing” in which a flaw of known size (length and cross-section) is introduced into a standard ASTM, four inch coupon and subjected to tensile loading as follows; 1) load to 100% proof stress (just short of yield) at room temperature, 2) load to tanking/prelaunch stress levels for seven cycles at cryogenic temperatures (liquid nitrogen bath), at 85% of proof stress, 3) load to flight stress levels at cryogenic temperatures (to demonstrate cryogenic strength enhancement) at 104.8% of proof, 4) repeat items 2) and 3) three more times. The sample is then pulled to failure and must pass the specification requirements. This procedure reflects the requirement for the SLWT to be capable of four full mission lives.

#### **Inspection**

In addition, a requirement was imposed for dual inspector dye-penetrant inspection of all parent material and formed parts, conducted by Level III inspectors (highest qualification). The inspection procedure for parent material was subsequently eliminated based on extensive inspection history which failed to identify any defects which would represent a safety of flight concern. The decision to eliminate this particular inspection was reviewed and approved by the MSFC Fracture Control Board.

### **3.1.2 Independent Assessment of Mitigation Approaches**

#### **Aerospace Safety Advisory Panel**

The ASAP provided periodic oversight of SLWT program developmental issues. The following paragraphs provide insight to the rigor of the ASAP review activity.

#### **ASAP 1996 Annual Report Finding 16 / Recommendations 16a-c**

##### **Finding 16**

The 2195 aluminum-lithium alloy used in the tank walls and domes of the new SLWT has lower fracture toughness at cryogenic temperatures than was anticipated in the design. To compensate for this potentially critical shortcoming, NASA has limited the pressure used in the full tank proof test and has recognized that the acceptance of each SLWT for flight is highly dependent on far more stringent quality control of the material and processes used to manufacture the SLWT than is required for the current external tanks.

##### **Recommendation #16a**

Assure that the acceptance tests for the 2195 material and the quality control procedures used in the manufacture of each SLWT continue to be sufficiently stringent, clearly specified, conscientiously adhered to and their use unambiguously documented.

##### **NASA Response**

*The Space Shuttle Program (SSP) and MSFC will continue to ensure that material acceptance testing and quality control procedures used in manufacturing of SLWT's are of sufficient quality to validate that each tank is fully in compliance with all program requirements and is safe to fly.*

##### **Recommendation #16b**

The criticality of these quality control operations makes it mandatory for NASA to retain buyoff of the results of those fabrication operations and tests that are essential in determining SLWT safety.

##### **NASA Response**

*The SSP and MSFC will retain approval of the quality control program and changes to that baseline.*

##### **Recommendation #16c**



As quality control data on the size of flaws detected in 2195 materials are collected, they should be used in an updated analysis of the SLWT structure, because it may permit the verifiable spread between flight limit stress and proof stress to be raised above that presently reported.

## **NASA Response**

*The simulated service database has been developed from data collected on fracture specimens with flaws which are 0.175 inch long. The data verify a 2.9 percent positive spread between the flight and proof-test conditions. Using the demonstrated flaw detectability level for our nondestructive evaluation dye penetrant process (0.086 inch long) would increase the spread to approximately 14 percent. Because of uncertainties, it is NASA's standard policy to use a factor of two on our flaw detectability limit. This methodology provides the proper risk allocation between nondestructive evaluation capability and proof test levels. The use of a flaw size of 0.175 inch for the simulated service test is conservative for the SLWT.*

The ASAP report continues: "NASA is taking extra precautions to assure that errors in manufacture can be detected. For example:

- Each sheet and plate of procured 2195 aluminum lithium material is inspected by ultrasound at the vendor, where flaws as small as 0.047 inch can be detected, and a flaw of 0.078 inch is cause for rejection. (OSMA Note: Any detectable flaw is cause for rejection).
- Before and after forming, (OSMA Note: As mentioned above dye penetrant inspection is now performed only after forming) the entire surface of each tank element is subjected to dye penetrant inspection with two pair of experienced and qualified eyes looking for flaws. Flaws as small as 0.086 inch have been shown to be detectable. Any detected flaw is cause for rejection."

All ASAP recommendations have been fully implemented and members of the ASAP team supporting the SLWT Design Certification Review on September 28, 1997 expressed satisfaction that the design is safe and the program is prepared to proceed. It is worth emphasizing that ASAP has consistently voiced concern that the SLWT program must remain vigilant in assuring flight critical manufacturing process control (1996 Annual Report):

"Obviously, strict adherence to established procedures is required at every step of this process. Once successful, complacency cannot be tolerated in the production of subsequent tanks"

## **Verification Team**

The Verification Team has also been heavily involved in parent material issues. Chapter 2 of the Odom Report, ("Final Report of the Super Lightweight Mission Success Team" report, July 1994) is devoted to issues associated with parent material properties, in particular

demonstration of Fracture Toughness Ratio (FTR); the ratio of cryogenic fracture toughness to room temperature fracture toughness. The Verification Team activity, extending from the Odom report, incorporated close partnership with the LM Fracture Control Board and the MSFC Fracture Control Board. These independent teams of technical experts provided close examination and rigorous scrutiny of all material acceptance rationale. The Verification Team documented and tracked safety and risk management issues and assured closure of any item affecting flight safety.

## **3.2 Issue: Manufacturing (Weld & Weld Repair)**

As mentioned above, every SLWT has over 3000 feet of welding. The weld land thickness ranges from  $t=0.140''$  to  $1.00''$ . Three welding techniques are employed: (Gas Tungsten Arc Welding (GTAW), Variable Polarity Plasma Arc (VPPA), and “Soft” Plasma Arc (SPAW). With 3000 feet of weld, it is essential to assure that welds are free of defects which could become safety of flight issues.

### **3.2.1 Mitigation Approaches**

The SLWT program has implemented a rigorous series of demonstration requirements for welding and weld repair processes involving the production of verification panels to demonstrate manufacturing capability and the fidelity of the completed weld or weld repair.

#### **Weld Repair Strength Verification**

Weld repairs are frequent. The first SLWT will have on the order of 600 weld repairs. This is comparable to the number of repairs on the early 2219 External Tanks. The current weld repair rate on the 2219 tanks is on the order of 150 repairs per tank.

Initially, weld repair strength verification testing was conducted with one inch wide coupons (cut from the five inch long repair weld) pulled to failure to determine ultimate strength. As the SLWT development program evolved, other test data revealed that repair welds actually did not have the strength observed in the one inch coupon tests. Indeed, it was determined that residual transverse forces were “stored” in the weld due to solidification shrinkage, resulting in the weld repair being weaker than the initial weld. The one inch wide coupons, in effect, released the residual stress and consequently did not show degraded strength performance. In late 1994, the SLWT program initiated efforts to more accurately evaluate the global effects of a local repair. Subsequently, an effort was undertaken to increase the strength of the repair weld and establish a methodology and criteria for identifying acceptable weld repairs.

## **Planishing Weld Repair**

The program used the process of hammering (peening) or cold forming, referred to as “planishing” to flatten the weld repair geometry in a way that residual stresses were redistributed, thus eliminating localized areas of high residual tensile stresses. The program established a 70% to 110% target for recovery of shrinkage as an indicator of strength recovery. It was also observed that planishing “work hardened the joint” further increasing strength.

## **Weld Repair Sensitivity Study and Weld Allowable Data Base**

Recognizing the inadequacy of one inch coupons the SLWT program conducted a sensitivity study involving 150 to 200 “wide panel” tests each test using 19 inch wide panels, of a given thickness (variable), which were repair welded a certain number of times (variable), then planished to a particular degree of recovery (variable). Based on the sensitivity testing a “standard repair” was defined as a testing norm for use in developing the “weld allowable” data base. The standard repair was defined as a five inch long, “R5” (where R5 indicates five repair welds, each one over the previous), in plate 0.32 inch thick and planished to a recovery value in the range 70% to 110%.

The weld design value (“weld allowable”) program tested on the order of 600 to 700 wide panels, including specimens representing all thicknesses of welds in the tank and testing to failure for both room temperature and cryogenic test conditions. The baseline “standard repair” was uniaxially loaded to failure for statistical samples of 30, for room temperature, and 20 for cryogenic temperatures. These tests provided a reasonable statistical knowledge of the variation of repair weld strength performance (one standard deviation on the order of 2 ksi). Additional tests were then conducted with other thickness material with reduced sample sizes (n=5 to 10). This body of testing forms the “weld allowable data base”.

## **Out of Family Weld Repair**

Weld repairs do not always conform to the criteria of “standard repair.” In some cases many more repairs are necessary or the length of the repair is longer than five inches, or planishing recovery is less than 70%. In such cases a sample of three wide panels are tested to failure to determine whether or not strength performance is within the range of the weld allowable data base. If this limited sample demonstrates similar strength values to the well characterized “weld allowable” population, and the lowest test strength value meets or exceeds the appropriate weld allowable, typically on the order of 30 ksi (room temperature), then the weld repair is considered an in-family repair that is acceptable and safe.

## **Wide Panel Testing**

Wide panel testing used a fracture screening process similar to that employed in the parent material acceptance process. The testing protocol is designed to demonstrate that a detectable crack or flaw will not propagate under the stress of four simulated life cycles of tensile loading as described below:

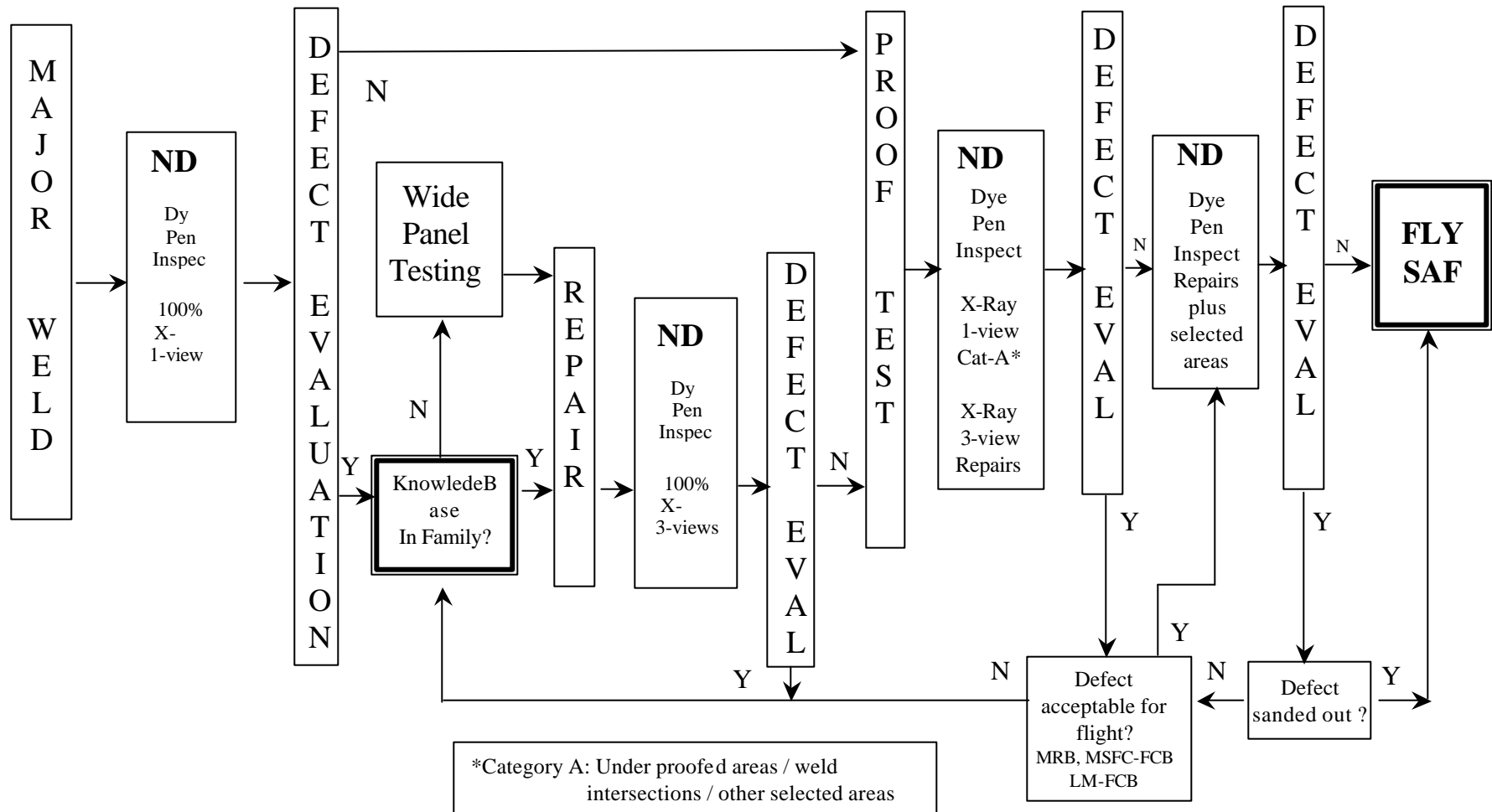
1) load to 100% proof stress (just short of yield) at room temperature, 2) load to tanking/prelaunch stress levels for seven cycles at cryogenic temperatures (liquid nitrogen bath), at 85% of proof stress, 3) load to flight stress levels at cryogenic temperatures (to demonstrate cryogenic strength enhancement) at 104.8% of proof, 4) repeat items 2) and 3) three more times. The sample is then pulled to failure and must pass the specification requirements. This procedure reflects the requirement for the SLWT to be capable of four full mission lives. This testing demonstrates the ability of the panel to provide limit-load (plus margin) strength performance without cracking, with an induced reference flaw size.

## **Reproof / Reinspect After Repair Weld**

Figure 3.1 provides a flow of the steps involved in assuring the fidelity of welds and repair welds on the SLWT. It is important to note that all repair welds are subjected to intense evaluation. Each repair weld is x-rayed at three different angles, and subjected to dye penetrant NDE inspection. Following these tests, the pressure vessel is proof tested to verify the acceptability of the tank. Then a final “targeted” x-ray inspection is conducted for historic problem areas, areas of the tank not fully loaded during proof tests, all weld repairs, and all weld intersections to verify that the proof test did not “open up” any defects that were below the NDE threshold of detectability. Any out of specification condition is recorded in a Non Conformance Document (NCD) which requires material review board (MRB) disposition. The disposition must have the concurrence of NASA S&MA and NASA S&E. The weld repair risk mitigation process builds confidence that the completed SLWT has no unacceptable defects and is acceptable for flight..

As seen in the figure 3.1, the SLWT program uses the “Defect Knowledge Base” as the central authority for deciding whether or not an observed defect is: 1) acceptable “as is”, 2) meets rigorously defined criteria to permit “in family repair”, or 3) represents something “out of family”, which requires testing and analysis sufficient to define a new weld repair protocol. The “Defect Knowledge Base” is then coupled to a multi-step verification process to assures the fidelity of weld repairs.

# SLWT Weld Defect - Risk Management Flow



## **Weld Repair Risk Management Example**

An example of the rigor of the SLWT analysis and review process is the approach taken when two very small subsurface flaws (0.030" and 0.045") were detected by X-ray on the ET97 LH2 tank after its final proof test. Repair and retest were considered, but the risk of two additional heat repairs was considered greater than the acceptance of these flaws. Before the flaws were considered for acceptance, a rigorous analysis was performed which showed that these flaws would survive over one thousand mission lives of seven propellant loading cycles and one flight loads cycle. For conservatism, the apparent radiographic flaw length was doubled for the analysis to compensate for the uncertainty involved in sizing flaws by X-ray. Since the program requirement is to be good for four mission lives, the capability of these flaws was more than 250 times the requirement. Further, the critical initial flaw size in the areas of each of the flaws is more than 10 times the apparent flaw length and this analysis was performed using a surface flaw rather than an imbedded flaw which is a more conservative approach. This determination was approved by the SLWT material review board, the LMC Fracture Control Board, and the MSFC Fracture Control Board which included representation from a JSC fracture control expert (Glen Ecord). The MSFC Fracture Control Board findings were documented to the project in their letter ED21 (ED25-97-73) dated October 30.

### **3.2.2 Independent Assessment of Mitigation Approaches**

#### **Office of Safety and Mission Assurance**

OSMA supported all IAR activity and engaged the SLWT program in discussions concerning technical safety and risk management issues throughout the program life-cycle. One example of OSMA involvement in the area of weld repair was the SLWT consideration of options for addressing the problem of intersection cracks (IC) observed in certain weld configurations, a topic of review at the 1997 IAR. Based on OSMA concerns and the need for better understanding the intersection crack phenomena, a review was held at NASA Headquarters in June of this year. At the same time the SLWT program's ongoing IC elimination initiative identified a potential solution. Testing showed that intersection cracking can be eliminated, almost entirely, through the substitution of 2219 ring frames for 2195 ring frames, and modifications to the welding techniques (dual cover vs. single cover weld passes and vertical, up oriented VPPA welding).

#### **Ongoing Challenges and Problem Solving in the Welding Arena**

Because of ongoing challenges in development of welding techniques and processes, the once-a-year independent assessment activities of the IAR and ASAP were not able to provide "real time" input to problem identification and resolution activity. Rather the team of LM, Reynolds Aluminum, MSFC, the LM and MSFC Fracture Control Boards and the Verification Team

were all involved in assessing and addressing welding techniques and the goodness of the resulting weld.

### **3.3 Issue: Design Verification Elements And Complexity**

Design verification concerns have been at the center of SLWT safety and risk management activities and have been a principal focus of independent assessment activity. The following paragraphs provide a summary of design verification approaches used for each of the principal SLWT elements.

The SLWT design verification approach operates from a bottom-up assessment of component failure modes and requires capability demonstration of each component, by test or linked to test data. In very few cases (e.g. LOX tank barrel, LOX tank aft ogive, and aft end of intertank thrust panel)) this ground rule cannot be satisfied and design verification must be demonstrated through a combination of analysis, test, heritage (existing flight and test data), and simulation modeling. These three cases represented design and material changes where verification “by testing” was deemed unrealistic. The technical complexity and physical requirements of the test would have required time and resources unavailable to the SLWT program. For these cases, the safety factor was increased to 2.0 and a second, independent analysis was required. While extraordinarily rigorous, the “combination verification” sometimes complex rationale creates a dependency on fidelity of analyses, goodness of modeling assumptions, absence of unknown synergistic effects and applicability of component testing data. This concern is mitigated by the use of conservative considerations in analysis and test. This body of conservative practice is also summarized below.

#### **3.3.1 Mitigation Approaches**

As mentioned above, the SLWT program design verification program is test-based. Every effort has been made to build verification rationale on demonstrated test data, either unique to the SLWT program, or through applicable testing performed for the existing Light Weight Tank program.

#### **LO2 Tank Design Verification: Complementary Elements:**

The LO2 tank was verified using a combination of test and analysis. In order to mitigate potential tank buckling concerns designers decided to maintain the current structural ringframe stiffness. Component testing to failure was initiated for multiple sub-systems, such as the slosh baffle beaded web. The fidelity of several LO2 tank design elements was independently verified by analyses conducted at the Langley Research Center. The LO2 tank aft dome stability was verified in the Aluminum Lithium Test Article (ALTA) program. Other important elements in the overall design verification included the work to characterize the parent material properties and develop welding and weld repair allowable data bases.

### **Intertank Design Verification: Complimentary Elements**

The intertank was also verified using a combination of test and analysis. In order to mitigate potential tank buckling concerns designers decided to maintain the current structural ringframe stiffness, thrust panel material and SRB beam design. Component testing to failure was initiated for multiple sub-systems, such as the skin stringer/joint, the beaded web, and the thrust panel. It is worth noting that early tests of the skin-stringer assembly resulted in skin buckling (prior to the required level), and led to design improvements which eliminated the problem. Independent analyses were conducted using the MSFC finite element stability model to verify aft thrust panel performance. The overall design was also supported by use of MIL-HANDBOOK 5 materials allowables information.

### **LH2 Tank Design Verification: Complementary Elements**

Buckling rather than strength represents the biggest challenge for structural designers. Buckling and the resultant orthogrid delamination result from shear and compression loading of a structure with insufficient stiffness.

The LH2 tank was verified using a combination of test and analysis. In order to mitigate potential tank buckling concerns designers decided to maintain the current structural ringframe stiffness. Component testing to failure was initiated for multiple sub-systems, such as the orthogrid panel cryoflex tests in which bi-axial loads were introduced to assess stress concentrations and validate cryogenic performance of the NASTRAN structural design model. The ALTA program demonstrated the stability requirements for most of the LH2 tank barrels with the remainder being demonstrated by protoflight testing. In order to verify the design and production fidelity of LH2 tanks, the SLWT program will subject every production tank to a protoflight testing regimen which will demonstrate longeron stability and aft dome stability. Supporting the LH2 design verification is the previously cited work performed in parent material characterization and development of welding and weld repair allowables.

### **Tanking/Detanking Test at KSC**

A test plan has been developed to tank/detank the first SLWT with the primary function of providing a propellant loading demonstration. The resulting temperatures and pressures will be monitored by KSC, including LM engineers. The results will be correlated to the analytical Main Propulsion System predictions and the historical database. The six (6) ET/SRB struts will be strain gauged to allow correlation of the “pinch load” values.



## **Conservative Assumptions and Philosophy to Offset Design Verification Complexity**

Analysis assumptions were made in a safety-conservative fashion employing the following:

- Maximum loads were combined with maximum pressures to achieve a worst case;
- Used limit/load pressures for pressure relieving scenarios, used limit minimum pressures for stability calculations;
- Used MIL HANDBOOK 5 “A Basis” assumptions (or NASA/MSFC) material property values;
- Used minimum pressure vessel thickness for pressure vessel failure modes;
- Used maximum drawing peaking/mismatch for generic weld analysis;
- Used verified “equivalent cylinder”, which is conservative versus NASTRAN non-linear analysis for failure modes;
- Used maximum principal stress and not “Hencky Von-Mises” strength failure theory for flight analysis. (Henky Von-Mises theory projects an increase in ultimate tensile strength when a structure is loaded in a bi-axial fashion)

## **Other examples of Conservative Design Engineering and Analysis**

- SLWT “Durability and Damage Tolerance” approach, set out in the MIL-Q-1530 specification assumes a flaw exists in every structural component at a size just below the detection threshold of NDE capability with assumed worst case location and orientation.
- Tank is designed for 3-engine 106% power rating (as well as two engines at 109% for abort cases) aerodynamic and structural load environment.
- Factor of Safety (FOS)
  - FOS = 1.25 for areas on the tank where the load environment is well understood;
  - FOS = 1.40 for areas of the tank where the load environment is less well understood;
  - FOS = 2.0 for structural areas of the tank not verified by test.
- 2195 aluminum lithium has approximately a 10% increase in stiffness at cryogenic temperature and a fracture toughness ratio greater than 1.0.
- The 115% structural verification protoflight test is conducted at ambient temperatures for each tank.
- 6'x6' flat plate cryogenic load testing is a “worst case” delamination scenario, as a curved section would have greater resistance to orthogrid delamination.

## **Verification of Analytical Models and Methods**

The success and safety of the SLWT is dependent on the accuracy and margin contained in analytical models and methodologies employed in the design process. The models and methods have been verified through, 1) comparison of model or method predicted structural response with measured structural responses from numerous test programs, 2) comparison of primary design model predicted response with predictions from other independent analytical models.

### **Analytical Models and Methods**

The SLWT program employed a finite element analysis NASTRAN program to predict and analyze structural load distributions. Other analytical methods were used to predict buckling and ultimate failure (closed form or standard structural analysis techniques). The SLWT NASTRAN model is the same pedigree as models used throughout the external tank program life. NASTRAN model analyses correlated well with strain gauge data acquired in previous external tank development programs (Standard Weight Tank and Light Weight Tank). Building on this heritage of safety and mission success, the SLWT program set out to demonstrate the model's ability to predict the load distribution throughout the redesigned tank structure for various loading cases and most importantly (along with other techniques described above), predict where and when a structure will fail for a given loading scenario.

The SLWT NASTRAN modeling code and analysis techniques have been validated through extensive correlation of strain gauge measurement information acquired during 1) the Aluminum Lithium Test Article (ALTA) program, 2) during protoflight tests conducted with each LH2 tank, and 3) in component testing.

### **Model/Method Verification through Test: ALTA**

In the case of the ALTA, over 700 strain gauges were deployed to acquire load distribution information through the various ALTA test scenarios including ultimate failure. The NASTRAN predicted load distribution correlated well with observations, falling within 5 % of measured strain gauge values in the regions of the test objectives. This conformity is considered excellent within the norm of structural design activity. The closed form cylinder analysis technique predicted the failure with an appropriately conservative margin. The model predicted failure at 126.5% of limit load, ultimate failure actually occurred at an equivalent load factor of 218%, following a period of extensive skin buckling and non-linear behavior. This degree of conservatism is appropriate when considering the non-linear and less well behaved mechanics of stability failure.

### **Model/Method Verification through Test: SLWT-1**

In the case of the SLWT-1 LH2 tank , loads were introduced for two protoflight loading scenarios, and 5 proof testing scenarios. Again, 700 strain gauges were deployed and measured induced loads which correlated extremely well with NASTRAN predictions, showing correlations, again within 5%.

### **Model/Method Verification through Test: Cryogenic Performance Test**

The cryogenic test panel behaved as predicted by the NASTRAN model, achieving agreement within 5% between strain gauge measurements and predicted response.

### **Model/Method Verification through Test: Component and Coupon Testing**

Component testing “to capability”, was performed on 13 different subassemblies having either a design or material change, (e.g. intertank skin/stringer-joint compression tests, frame beaded web tests, and the “cryoflex” (cryogenic environments test). In each test, results showed article failure strength was well predicted by analytical techniques with some conservatism (e.g. 20-40% for beaded webs, 2-3% for intertank skin-stringer tests). There was however one test where the test article skin buckled which required a design change which subsequently passed the test. Welding and material qualification (pull to failure) testing results were also shown to agree well (20% conservatively) with BOSOR (buckling of shells of revolution) analytical predictions.

### **Model/Method Verification through Comparison: Langley Research Center (LaRC) Finite Element Model**

Independent analytical models were used to validate the NASTRAN results in the three cases where combination analysis and coupon testing was used to verify structural integrity. A LaRC finite element model was used to validate the NASTRAN results for the LO2 tank barrel section and the LO2 tank aft ogive assuring in each case, a Factor of Safety greater than 2.0.

### **Model/Method Verification through Comparison: MSFC Finite Element Model**

The MSFC finite element analysis model was employed to verify predicted loads and capability of the intertank aft thrust panel. The two models (NASTRAN and MSFC finite element) agreed well and predicted structural Factors of Safety greater than 2.0.

### **Environmental Loads Model (Load Sets)**

Space Shuttle Program Level II (Johnson Space Center) provides the SLWT program with Boeing North American (Rockwell) generated load sets. The SLWT program worked in an iterative process with Level II (sending the SLWT structural model to Downey to support

system level loads calculations, receiving back the overall Shuttle system load environment, then refining the design as necessary to provide design margin, then sending the revised structural model back to Downey to support the next round of environmental load simulation.) The pedigree of the Level II environmental loads/ systems loads model is based on actual flight Orbiter strain gauge data, and early wind tunnel testing information.

### **3.3.2 Independent Assessment of Mitigation Approaches**

#### **Verification Team Reviews**

Three principal technical review teams evaluated the early SLWT test and verification strategy. To a large extent, their activities were conducted in parallel which provided for constructive interaction and eventual synthesis of technical issues.

An in-house, Martin Marietta review was conducted by former MMSS president Rick Davis during spring-summer 1994. Rick Davis, strongly recommended conducting a full-up cryogenic test. Concurrently, a team led by Jim Odom was chartered to “assess the feasibility” of the overall SLWT development program. A NASA MSFC Engineering review was conducted by Bob Ryan during the summer of 1994. This team developed an approach combining analysis and testing with rigorous modeling of performance. The Bob Ryan team interacted with both the Rick Davis and Odom teams, and worked closely with the SLWT program management team to develop the ultimate SLWT test and verification approach. An OSMA review led by Dan Mulville was conducted in the summer-fall 1994. The OSMA report concurred with the recommendations from the Odom and Davis teams to expand the planned structural verification activity.

The “Verification Team” (follow-on for the Davis/Odom review activity) provided ongoing, in-depth technical review capability to the SLWT program. Based on a review of the proceedings of Verification Team presentations and discussions it was evident that the SLWT program is systematically involved in risk identification, risk ranking, and risk mitigation. An example (Verification Team meeting, May 18-19, 1994) is provided below:

#### Ranked Safety of Flight Issues (a quantitative ranking methodology was employed)

- LH2 Barrel 1 Panels at Longerons--Stability Failure Modes
- LH2 Barrel 2 Panels at Longerons--Stability Failure Modes
- LH2 Tank Barrel 4 Panels--Stability Failure Modes
- LH2 Barrel 3 Panels--Stability Failure Modes
- LH2 Barrel 2 Panels--Stability Failure Modes
- Forward Ogive Gores--Stability Failure Modes
- LO2 Tank Barrel Panels--Stability Failure Modes
- Skin Stringer Panels--Stability Failure Modes
- LO2 Tank Dome Gores--Stability Failure Modes

For each safety of flight risk area, “ideas for risk reduction were collected and actions assigned to expand upon all ideas with promise.” The SLWT “Verification Philosophy” was hammered home time and time again. The philosophy was:

- “Verify by test, for each structural element, the integrity of the structure;
  - Test can demonstrate structure will withstand ultimate loads, or test can demonstrate structure will withstand limit load and validate analysis accuracy and conservatism used to extrapolate to ultimate load;
  - Test can be omitted if FS greater than or equal to 2.0 (generally applied to secondary structure);
  - Test not required if similar, more critical, structural element has been test verified (i.e., gore panels, barrel segments);
  - Test completion is precursor to flight or critical design condition (e.g., stacking, prelaunch, etc.);
  - Test articles will be built on production tooling with production processes;
  - Test articles will be fabricated from material acceptable for production hardware
- Deviations from above philosophy may be acceptable based on quantifiable rationale.”

Verification Team meetings were thorough in their coverage of SLWT structural safety-of-flight issues, well documented, had clear conclusions and action items, and good follow-through from one meeting to the next. As discussed in introductory remarks concerning IA activity, the Verification Team has been a real time risk management participant identifying and assuring satisfactory closure of issues.

### **OSMA (Mulville) Review 1994**

OSMA was asked by the Program Management Council to conduct an independent assessment of the SLWT design verification activity in mid-1994, leading to a report in November of that year. This report concluded that the current SLWT protocol met the intent of NASA policy but strongly urged that additional testing be incorporated to reflect structural performance at cryogenic temperatures. In a December 9, 1994 letter to Acting Deputy Administrator, the AA/OSMA said,

“Although a full-up structural test article is not required, the opportunity to better demonstrate the performance of ‘as welded and repaired’ structure as proposed by the engineering change proposal now under consideration will further reduce program risk. Consequently we support the engineering change proposal’s (ECP) acceptance.”

The OSMA review team concluded the SLWT project test and verification plan would be acceptable “upon closure” of:

#### **A. Material characterization**

- B. Weld characterization
- C. Successful correlation of analytical modeling with:
  - 1. Component coupon test data
  - 2. Sub-assembly, Aluminum Lithium Test Article performance data (140% proof test, then test to failure)
- D. Proof testing of the LO2 and LH2 tanks: a room temperature pressure proof test at an analytically equivalent (adjusted) pressure of 105% of fracture basis limit load (production verification test)
- E. Protoflight testing of the LH2 tank: 115% static loads applied to Orbiter and Solid Rocket Booster attach points (production verification test)
- F. Resolution of cryogenic loading concerns

The review team recommended that the Shuttle program evaluate the ‘desirability’ of instrumenting the first SLWT to determine pre-launch and/or flight loads. This non-safety-of-flight recommendation was considered but ultimately set aside. The program decided against implementation based on strong confidence in the knowledge of the expected load environment and a belief that analytical modeling and tests have provided equivalent insight into flight load response.

The review team also recommended considering a cryogenic impact assessment test proposed in a Martin Marietta ECP. This test involved bi-axial loading of a 6'x6' flat orthogrid plate at cryogenic temperatures. This test was designed to verify the performance of 2195 in the as-welded and as-repaired configuration, as well as to verify adhesion of SOFI thermal insulation. Completion of this test was deemed desirable in order to reduce the risk associated with incorporation of new materials, design and fabrication methods in the SLWT.

The cryoflex panel testing was, in fact, implemented and, as discussed above, showed excellent agreement between the NASTRAN predicted load distribution and strain gauge measurements. All of the OSMA recommendations were implemented or accepted by OSMA as closed.

### **ASAP Findings and Recommendations / SLWT Program Response**

The ASAP, led in its technical evaluation by Melvin Stone, took exception (1995 report) with the LO2 tank aft dome design verification approach: “The liquid oxygen tank aft dome gore panel thickness of the SLWT has been reduced significantly on the basis of analyses. To stiffen the dome a rib was added. The current plan to verify the strength of the aft dome involves a proof test to only limit load. Buckling phenomena cannot be extrapolated with confidence between limit and ultimate load.” ASAP recommended that “the SLWT aft dome should either be tested to ultimate loads or its strength should be increased to account for uncertainties in extrapolation.”

NASA agreed with the recommendation and added an aft dome test to the ALTA test program (successfully completed).

### **3.4 Issue: Production Verification**

In addition to the manufacturing process development issues identified above, and given the sensitivity of critical manufacturing processes, it is evident, that full scale production verification testing is important to assure the individual tank is free of defects.

#### **3.4.1 Mitigation Approaches**

##### **Production Verification Testing**

##### **LH2 Protoflight Test**

- Each production LH2 tank receives a prototype test which imposes 115% static limit load. The test verifies buckling stability. The loads are introduced at the Orbiter and Solid Rocket Booster attach points using worst case static load values.
- Each LH2 and LO2 tank undergoes a room temperature pressure proof test at an analytically equivalent (adjusted) pressure of 105% of fracture basis limit load. These tests provide an even higher strength verification and a flaw screen (fracture control acceptance test). The test process verifies weld integrity, fracture strength, and addresses workmanship issues. All welds not subject to operational load are x-ray inspected.

##### **Non Destructive Evaluation**

The SLWT program uses x-ray and dye penetrant testing and inspection (along with proof testing) as a means to verify the integrity of each SLWT pressure vessel. Process requirements are the most stringent possible.

##### **Parent Material**

Parent material NDE includes ultrasonic testing of all raw stock.

##### **LO2 Tank**

LO2 NDE activity includes: penetrant inspection of pressure vessel membrane, visual inspection, X-ray and penetrant of welds pre-proof, and X-ray of selected welds, weld intersections, and all weld repairs post proof.

##### **Intertank**

Intertank NDE includes: penetrant inspection of all formed parts, and visual inspection of assembled hardware.





## **LH2 Tank**

LH2 NDE involves: penetrant inspection of pressure vessel membrane, visual inspection, X-ray and penetrant of welds pre-proof, and X-ray of selected welds, weld intersections, and all weld repairs post proof

### **3.4.2 Independent Assessment of Mitigation Approaches**

Production verification independent assessment activity involved all of the various groups discussed above and overlapped in part with material acceptance activity and design verification as well as welding and weld repair. This specific area does provide an opportunity to highlight another key partner in the independent assessment process, the MSFC Science and Engineering Directorate.

#### **MSFC Science and Engineering Directorate**

Previous discussion of the MSFC Fracture Control Board recognized, in effect, the significant role of numerous experts in metallurgy, material properties, fracture mechanics, and test and evaluation. The nature of their “independence” was based in their professional adherence to their science, and unyielding technical rigor. Another “inside” but independent technical forum was the NDE community at MSFC. NDE issues were worked very hard at milestone reviews and were in fact outstanding issues of discussion, and eventual resolution, at the Design Certification Review.

## **4.0 Summary & Conclusions**

### **4.1 Safety and Risk Management Strengths**

- Lockheed Martin Michoud has an embedded safety and risk management philosophy evidenced by formal processes which address all of the risk management elements contained in NPG 7120.5A.
- The SLWT has had the benefit of extensive external independent assessment.
- Independent assessment came from outside the agency, outside the project, and outside the center. Independent technical analysis was provided by MSFC S&E, and Langley Research Center.
- The SLWT program has been extremely responsive to independent assessment recommendations.
- Conservative assumptions have been employed throughout the design verification and analysis process.
- Strengths also include design heritage, and the culture of human space flight which has been producing human rated systems for more than 30 years.

### **4.2 Closure of Design Certification Review Risk Management Issues**

All “Review Item Discrepancies” (RIDs) identified at recent Design Certification Review for the SLWT have been resolved between members of the DCR technical review teams and cognizant MSFC Science and Engineering, Safety & Mission Assurance, and SLWT program managers. Closure of the RID paperwork is in progress at this time.

### **4.3 Conclusion**

The OSMA SLWT safety and risk management evaluation team finds that risk issues and other concerns identified by the SLWT program and numerous independent assessment teams have been properly managed and dispositioned.

Given the conservative design and test approach, the maintenance of safety margins, and extent and rigor of independent assessment and independent technical analyses we find the SLWT design is safe. With continued strict adherence to critical manufacturing process stability, capability and control (especially weld repair allowables) we are confident that the SLWT will operate safely.



## **Appendix A**

### **Chronology of Milestones and Independent Reviews**

- Nonadvocacy Review-January 20, 1993
- Aerospace Safety Advisory Panel (ASAP) - May 12, 1993
- MMC Mission Success Review - October 1993
- S&E Review - February 23, 1994
- NASA / Martin Marietta Independent Reviews - April 17-23, 1994
- 1994 Independent Annual Review - May 18-19, 1994
- Verification Team Independent Review - May 18-19, 1994
- Preliminary Requirement Review (PRR) - June 1994
- NASA / Martin Marietta Independent Reviews - June, 1994
- Aerospace Safety Advisory Panel - June 29, 1994
- ALTA Design Review - August 1994
- NASA / Martin Marietta Independent Review Report - October 1994
- Preliminary Design Review - November 1994
- MSFC Fracture Control Board - January 1995
- Start Fabrication of ALTA - February 1995
- Blue Ribbon NDE Review - April 3-4, 1995
- 1995 Independent Annual Review - April 10, 1995
- Verification Team Independent Review Follow-On - April 10-11, 1995
- NASA / Martin Marietta Independent Review Followup - May 30-June 1, 1995
- Start Fabrication of SLWT 1- June 2, 1995
- Space Shuttle Program Review - June 15, 1995
- Aerospace Safety Advisory Panel - June 14-15, 1995
- Critical Design Review - June 28, 1995
- Verification Team Independent Review Followup - August 1995
- Brewster Shaw Review - June 14-15, 1995
- Production Readiness Review - December 1995
- ALTA Proof Test - January 1996
- ALTA DD-250 - January 1996
- Verification Team Independent Review Followup - February 1996
- Tommy Holloway Review - April 19, 1996
- Aerospace Safety Advisory Panel - May 9, 1996
- 1996 Independent Annual Review - May 15-16, 1996
- NASA Independent Review of Extrusions - July 1996
- ALTA Ultimate Tests Complete - July 1996
- ALTA Capability Test Complete - September 6, 1996
- LH2 Tank Pre-proof Review - November 12-14, 1996
- Verification Team Independent Review Followup - November 25-26, 1996

- Review with Aerospace Safety Advisory Panel - March 20, 1997
- SLWT-1 LH2 and LO2 Tank Proof Test - March 25, 1997
- Space Shuttle Program Review - April 28, 1997
- 1997 Independent Annual Review - June 23-24, 1997
- Design Certification Review Phase I - June 24-26, 1997
- Design Certification Review Phase II - September 1997
- SSP Performance Enhancements DCR - October 22, 1997
- Lead Center Performance Enhancements DCR - November 13, 1997
- SLWT-1 DD250 - January 6, 1998
- First SLWT Launch - May 29, 1998

## Appendix B

### Compendium of Outside Participants in Independent Reviews

<u>Name</u>	<u>Affiliation</u>	<u>Expertise</u>
VERIFICATION TEAM:		
Glenn Miller	JSC	Structures Division
Dr. Michael Nemeth	LaRC	Structural Mechanics (Stability)
Robert Morra	LMC/Retired	Former Corporate Chief Engineer
Jackie Bunting	LMC/Astronautics	Director of Advanced Vehicles
Glen Ecord	JSC	Fracture Mechanics
PARENT METAL TEAM:		
M. H. Skillingberg	Reynolds	Aluminum Lithium
Dr. Alex Cho	Reynolds	Aluminum Lithium
M. M. Niedzinski	Reynolds	Aluminum Lithium
Cathy Bailey	Reynolds	Aluminum Lithium
Rich Greene	Reynolds	Aluminum Lithium
John Weritz	Reynolds	Aluminum Lithium
Dr Art Girard	Reynolds	Aluminum Lithium
Jeff Stewart	Reynolds	Aluminum Lithium
Dr. Chip Blankenship	GE Corp. Labs	Aluminum Lithium
Dr. Wayne Hayden	Oak Ridge N'tl Labs	Aluminum Metallurgy
Dr. Bill Brown	LeRC	Fracture Mechanics
WELD AND WELD REPAIR TEAM:		
Mac Roberts	LM-Denver	Welding
Doug Waldron	MDAC	Welding
Stan David	Oak Ridge N'tl Labs	Welding
Charlie Rabino	Sandia N'tl Labs	Welding
Dr. John Lippold	Edison Weld Institute	Welding
Dr. Pinsha Dong	Edison Weld Institute	Residual Stresses
Paul Fielding	Reynolds	Aluminum Lithium
Sam Gambrell	University of Alabama	Welding
Dr. Peter Romine	Ala. A&M Univ	Welding Controls
Dr. Ray Thompson	Univ of Al B'ham	Welding
Glen Adams	Univ of Arkansas	Welding
Dr. K. Soni	Univ of Chicago	Metallurgy
Dr Gene Goodwin	Oak Ridge N'tl Labs	Welding
Dr. Mike Cieslack	Sandia National Labs	Aluminum Welding
Larry Loecael	LMC/Astronautics	Aluminum Lithium Welding
Dr. Joe Pickens	LMC/Corporate Labs	Aluminum Lithium
Dr. Tim Langan	LMC/Corporate Labs	Aluminum Lithium
Dr. John Green	LMC/Corporate Labs	Aluminum Lithium
Larry Cramer	LMC Corporate Labs	Aluminum Lithium
Gil Braun	LMC/Astronautics	Aluminum Lithium
David Sisk	LMC/Astronautics	Cryogenic Tanks

ALCOA METALS QUALIFICATION TEAM (SECOND SOURCE OF ALUMINUM LITHIUM):

Robert Graham	Alcoa	Mgr Aluminum Lithium Casting
Dr Roberto Rioja	Alcoa	Aluminum Lithium Metallurgy
Greg Venema	Alcoa	Aluminum Lithium Rolling
Gregg Kruzynski	Alcoa	Aluminum Lithium Casting

BLUE RIBBON NDE TEAM:

Albert Birks	Thiokol	NDE
Steve LaRiviere	Boeing	NDE
Ed Generazio	LaRC	NDE
Don Hagemmaier	MDAC	NDE
Ward Rummel	LMC/Astronautics	NDE
Don Pettit	LMC/Georgia	NDE

BLUE RIBBON FRACTURE MECHANICS TEAM:

Roy Hampton	ARC	Fracture Mechanics
Royce Foreman	JSC	Fracture Mechanics
Jim Newman	LaRC	Fracture Mechanics
John Wagner	LaRC	Fracture Mechanics
Bill Brown	LeRC	Fracture Mechanics
John Shannon	LeRC	Fracture Mechanics

JIM ODOM TEAM:

Jim Odom	Applied Research Inc	Former ET Project Manager
John Crews	SAIC	Fracture Mechanics

RIC DAVIS TEAM:

Ric Davis	Retired Consultant	Former Head of MSS
Robert Morra	Retired Consultant	Former Martin Corp. Chief Eng.
Jackie Bunting	LM-Astronautics	Director of Advance Vehicles
Jack Nichols	Retired Consultant	Former ET Chief Engineer
Gayle Howell	Retired LMC	Former Director of SR&QA

(MSFC)

Larry Norquist	LM-Astronautics	Propulsion Engineering
Al Norton	Retired Consultant	Former VP Martin-Orlando
Art Welch	Martin Corporate	Former Head S&MA
George Rodney	NASA HQ	AA for S&MA

AEROSPACE SAFETY ADVISORY PANEL (ASAP):

Melvin Stone	ASAP	Former Dir. Of Structures, Douglas Aircraft
Paul Johnstone	ASAP	Former Sr.VP. Ops at Eastern Airlines
Ken Engler	ASAP	Former Chief Eng. At McDonnell Douglas
Sey Himmel	ASAP	Former Assoc. Dir. NASA LeRC



# NONADVOCACY REVIEW COMMITTEE:

Bob White	JSC	Systems Integ (Chair)
James McMahon	JSC	Structural Analysis.
J. Gunderson	Headquarters	Business Management
Patricia Watson	JSC	Space Station Prog. Office
J. Wagner	LaRC	Aluminum Lithium
Dr. A. Tessler	LaRC	Structural Design
Dr. J. Newman	LaRC	Fracture Mechanics
Dr. M. Card	LaRC	Structural Dynamics
R. Caudle	Headquarters	Resource Management
Mike Moore	JSC	Operations Assessment
Craig Carothers	JSC	Mission Integration
Keith Hudkins	Headquarters	Systems Integration
Mark Holderman	JSC	Systems Integration
Tom Perantie	JSC	Operational Assessment
J. Bennett	JSC	Metallurgy

## PRELIMINARY BUILD REQUIREMENTS REVIEW TEAM:

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Richard Ciepiela	LM-Astronautics	Director of Production Eng.
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Michael Jansen	JSC	Flight Mechanics
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Robert Lang	KSC	Head of Vehicle Engineering
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